98-15632 (82)
Translated from Russian

SERIYA: YADERNYE KONSTANTY, Vypusk 2, (1998), s. 58
(Series: Nuclear Constants, Issue No. 2 (1998), p. 58)

VALIDATION OF THE ABBN/CONSYST CONSTANTS SYSTEM.

PART 1: VALIDATION THROUGH THE CRITICAL EXPERIMENTS ON COMPACT METALLIC CORES

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VALIDATION OF THE ABBN/CONSYST CONSTANTS SYSTEM. Part 1: Validation through the Critical Experiments on Compact Metallic Cores. World-wide compilation of criticality safety benchmark experiments, evaluated due to an activity of the International Criticality Safety Benchmark Evaluation Project (ICSBEP), discovers new possibilities for validation of the ABBN-93.1 cross section library for criticality safety analysis. Results of calculations of small assemblies with metal-fuelled cores are presented in this paper. It is concluded that ABBN-93.1 predicts criticality of such systems with required accuracy.

Introduction

The ABBN/CONSYST constants system includes the ABBN-93 constants set and the CONSYST program which prepares these constants for calculations using recommended algorithms. They were certified as recommended data in 1995 by the State Information Service for Standard Reference Data (certificate No. 444, dated 1 August 1995). Unlike earlier versions of the ABBN constants, the ABBN/CONSYST constants system is recommended not only for fast power reactor calculations, but also for calculations for thermal neutron and intermediate neutron reactors, radiation shield, and criticality safety of the external fuel cycle, for calculating the radio-nuclide composition of spent fuel and irradiated materials, and for evaluating radiation damage to materials, etc. This recommendation was based on a thorough verification report [2] which was subjected to expert assessment by experienced specialists representing various fields and specialities in the nuclear power development area. In the interim, however, a large quantity of additional experimental data has become available, chiefly thanks to the activities of the International Critical Safety Benchmark Experiment Project (ICSBEP). Pursuant to these activities, the International Handbook of Evaluated Criticality Safety Benchmark Experiments [3] was issued (subsequently referred to as the Handbook) which contains detailed descriptions of carefully evaluated critical experiments performed in various countries. Russia too has made a major contribution to the Handbook.

The series of publications of which this article forms the first is devoted to a validation of the ABBN/CONSYST constants system through the experimental results collated in the above-mentioned Handbook. The main stimulus for this work was the need to validate the programs and databases used to evaluate nuclear safety in the external fuel cycle for the purposes of their subsequent licensing by Gosatomnadzor [Federal Nuclear and Radiation Safety Authority of Russia]. However, since nuclear safety calculations are performed using programs which solve the strict transport equation with a detailed description of the geometry (Monte Carlo method), many of the benchmark experiments used to validate criticality safety evaluation programs can also be used as benchmarks to validate constants' software. Such experiments include, in particular, critical experiments on compact cores carried out within the framework of nuclear weapons development programmes in the USA and Russia. A computational analysis of these experiments is given in this article. The calculations were carried out using the KENO-Va and KENO-VI codes employing the 299-group ABBN-93 constants (the version transmitted to the RSICC). For comparison, the results of calculations carried out using the MCNP program are also given with a detailed description of the energy dependence of the cross-sections based on the ENDF/B-V evaluated nuclear data library (computational instrument licensed in the USA for criticality safety calculations). The calculation results for foreign constants we took from the relevant foreign sources.

1. Critical assemblies with no reflector with an enriched uranium core

The results of a comparison of the calculated data with the experimental data are given below. The differences between the calculated value ($k_{c,i}$) and the experimental value ($k_{e,i}$) of the multiplication coefficient are shown as a percentage. The results generated by the CONSYST-KENO package are given, together with the error levels obtained in the evaluation of the experimental data which are given in the descriptions of the evaluations (see Ref. [3]). The experimental error levels ($\delta k_{e,i}$) are also shown as percentages with a "±" sign. Next, the statistical error level ($\delta k_{c,i}$) is given for the calculation result using the Monte Carlo method. This is shown in brackets and is expressed as a whole number of hundredths of a per cent. Thus, the value 0.36±0.16(7) means that the difference between the calculated and experimental values of k_{eff} is 0.36%, the error level of the experimental value is 0.16%, and the statistical error level of the calculation is 0.07%. Thus, the error level of the difference is $\delta k_i = \sqrt{\delta k_{e,i}^2 + \delta k_{c,i}^2} = \sqrt{0.16^2 + 0.07^2} = 0.175$.

The results obtained using the MCNP program and the ENDF/B-V constants are also taken from Ref. [3] for American critical assemblies, and from Ref. [4] for Russian critical assemblies. The latter source also gives the data obtained using the ENDF/B-VI library. These are also shown in the table. For the results obtained using the MCNP program, only the statistical error level is given; the experimental error level is not duplicated.

For an overall evaluation of the divergence between the calculation and the experiment, the following mean characteristics need to be calculated.

The expected root-mean-square spread of the divergence between the calculation and the experiment determined from the evaluated error levels of both:

$$\delta k_{\exp} = \sqrt{\frac{n}{\sum_{i=1}^{n} 1/\delta k_i^2}}.$$

The mean deviation of the calculation from the experiment:

$$\Delta k = \frac{\sum_{i=1}^{n} (k_{c,i} - k_{e,i})/\delta k_i^2}{\sum_{i=1}^{n} 1/\delta k_i^2}.$$

The observed root-mean-square spread of the divergence of the experimental data (root-mean-square deviation from the results of the calculation performed using the constants which yield the best match with the experimental data, i.e. $\Delta k = 0$):

$$\delta k_{cal} = \sqrt{\frac{\sum_{i=1}^{n} (k_{c,i} - k_{e,i} - \Delta k)^2/\delta k_i^2}{\sum_{i=1}^{n} 1/\delta k_i^2}}.$$

These formulae do not take into account possible correlations between the error levels of the various experiments.

These data show that the calculations using the ABBN-93 and ENDF/B-V constants underestimate k_{eff} by a quarter of a per cent. This underestimation is systematic and is almost twice the error level of each individual experiment. The exception is the assembly with 36% enriched uranium where the calculated value of k_{eff} is slightly higher than the experimental value.

If we exclude this assembly, which differs significantly from the remaining assemblies in both composition and neutron spectrum, the mean divergence increases to -0.29%, and the root-mean-square spread of the experimental data decreases to the level which would be expected working from the evaluated experimental error levels (the contribution of the statistical error levels of the calculated results is also taken into account, but it is not very significant). The results obtained by averaging for the six assemblies with high-enriched uranium are given in Table 1 in brackets. In this case too, the results obtained using the ABBN-93 and ENDF/B-V constants are practically identical. ENDF/B-VI yields a significantly larger divergence between the experimental and calculated data, but even here the root-mean-square spread calculated after correction for shifting of the calculated values relative to the experimental values is as would be expected from the evaluated experimental error levels.

Table 1. Uranium assemblies with no reflector

Experiment index from the Handbook	Location carried out	Experiment configuration	(k_c-k_e) in %, KENO ABBN-93	(k_c-k_e) in %, MCNP ENDF/B-V	(k_c-k_e) in %, MCNP ENDF/B-VI
IEU-MET-FAST-003	VNIIEF[1]	Sphere (36%)	+0.08±0.17(7)	+0.54(6)	+0.09(9)
HEU-MET-FAST-018	VNIIEF	Sphere (90%)	–0.14±0.14(7)	–0.16(5)	–0.37(6)
HEU-MET-FAST-008	VNIITF[2]	Sphere (90%)	–0.36±0.16(7)	–0.55(6)	–0.64(6)
HEU-MET-FAST-001	LANL	Sphere (94%) (Godiva)	–0.02±0.10(7)	–0.32(9)	
HEU-MET-FAST-007-01	ORNL	Parallelepiped (94%) 25x25x4 cm	–0.49±0.10(8)	–0.30(13)	
HEU-MET-FAST-007-019	ORNL	Parallelepiped (94%) 13x25x6 cm	–0.25±0.10(7)	–0.12(14)	
HEU-MET-FAST-015	VNIITF	Cylinder (96%)	–0.64±0.17(7)	–0.45(6)	–0.73(6)
Expected root-mean-square spread (δk_{exp})			±0.14	±0.14	±0.17
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			–0.25±0.22 –0.29±0.17*	–0.22±0.26 –0.29±0.14*	–0.43±0.52 –0.56±0.16*

* Values obtained without taking into account the data for the sphere of 36% enriched uranium.

From the above we may conclude that the set of experimental data obtained for the six assemblies with high-enriched uranium with no reflector at the four different institutes is internally consistent and indicates that calculations using the ABBN-93 constants (and the

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[1] All-Russian Research Institute of Experimental Physics

[2] Russian Federal Nuclear Center Institute of Theoretical Physics

ENDF/B-VI constants) underestimate k_{eff} for such assemblies by almost 0.3%. In future this divergence could be eliminated by correcting the constants, which would reduce the expected error level of the calculated prediction of the criticality of such systems to less than one tenth of a per cent.

2. Critical spheres made of plutonium with no reflector

Table 2 gives the calculation results for four critical assemblies with plutonium spheres with no reflector. The experiments were carried out at two different institutes. Two assemblies had a high plutonium-240 content (12% and 20%). The last rows of the table give the same mean characteristics as for the uranium critical assemblies.

As may be seen from the above data, the criticality of the plutonium spheres is underestimated in the calculations almost to a greater extent than the criticality of the uranium spheres. The calculations using ABBN-93 underestimate k_{eff} by 0.3%, those using ENDF/B-V by 0.4%, and those using ENDF/B-VI by 0.5%. All these shifts exceed the experimental error levels where evaluated values - judging from the root-mean-square spread of the experimental data - are certainly not overestimated (since the number of experiments is small - a total of 4, the fact that the root-mean-square spread is significantly smaller than the evaluated experimental error levels is no justification for asserting that the evaluated error levels are unjustifiably high). No correlation was found between the divergence and the plutonium-240 concentration.

Table 2. Plutonium assemblies with no reflector

Experiment index from the Handbook	Location carried out	Experiment configuration	$(k_c$-$k_e)$ in %, KENO ABBN-93	$(k_c$-$k_e)$ in %, MCNP ENDF/B-V	$(k_c$-$k_e)$ in %, MCNP ENDF/B-VI
PU-MET-FAST-022	VNIIEF	(2% ^{240}Pu)	-0.27±0.21(9)	–0.35(5)	–0.41(6)
PU-MET-FAST-001	LANL	(5% ^{240}Pu) Jezebel	-0.21±0.20(6)	–0.43(12)	
PU-MET-FAST-029	VNIIEF	(12% ^{240}Pu)	-0.53±0.20(6)	–0.56(5)	–0.57(6)
PU-MET-FAST-002	LANL	(20% ^{240}Pu) Dirty Jezebel	-0.22±0.20(9)	–0.15(14)	
Expected root-mean-square spread (δk_{exp})			±0.21	±0.22	±0.21
Observed mean divergence $(\Delta k \pm \delta k_{cal})$			–0.31±0.13	–0.38±0.15	–0.49±0.08

Doubtless a minor correction to the plutonium-239 constants used would bring the calculated data for k_{eff} into line with the experimental data to within the error limits of the latter. Correction of the uranium-235 constants would also bring about a better match between the calculation and the experiment.

3. Critical spheres made of plutonium in a high-enriched uranium shell

Table 3 gives the results of a comparison of the calculated and experimental data for two critical assemblies with compound cores made of plutonium and uranium. One of them, which was studied at LANL, had a central plutonium core (5% plutonium-240) and a high-enriched (93%) uranium shell 1.7 cm thick; in the other, which was studied at VNIITF, the plutonium core contained 9.3% plutonium-240 and the uranium shell, which was 2.3 cm thick, had an enrichment level of 89.6%.

Clearly, the nature of the divergences between the experimental data and the calculations using the ABBN-93 constants is as was to be expected here, working from the computational analysis of the pure uranium and pure plutonium bare assemblies: the divergence is greater than for the former and less than for the latter. This confirms further the conclusions drawn regarding the underestimation of k_{eff} in the calculations, and the desirability of correcting the constants by fitting the results to the critical experiment data. At the same time it should be noted that the calculations using the ENDF/B-V constants for these assemblies show an unexpectedly high level of agreement with the experiment: the divergences were lower than for both the uranium and the plutonium critical assemblies. However, since there were only two uranium-plutonium assemblies with no reflector this must be viewed as a chance effect. The fact that the root-mean-square spread (± 0.10%) is noticeably less than the evaluated experimental error levels and statistical error levels of the calculation (± 0.17%) would lead one to expect, despite the fact that these error levels are fairly close to the error levels for the determination of k_{eff} for the uranium (± 0.14%) and pure plutonium assemblies (± 0.22%), supports this view.

4. Critical spheres made of uranium-233 with no reflector in an enriched uranium shell

There are a total of three assemblies with metallic uranium-233 in the core. In two of them, the central uranium-233 core is surrounded by a spherical layer of metallic uranium-235 1-2 cm thick. The divergence between the calculation and the experiment for these assemblies are given in Table 4.

Thus, for compact assemblies with uranium-233 the calculations also underestimate k_{eff} by 0.4 ± 0.2% when using the ABBN-93 constants, and by 0.2 ± 0.2% when using ENDF/B-V. The ± 0.2% error level confirms our opinion that the experimental error levels ascribed to the experimental data, by comparison with the evaluated error levels for the plutonium assemblies and the assemblies with high-enriched uranium, are unjustifiably low. The high root-mean-square spread of the data, by comparison with the calculations using ENDF/B-V, indirectly support this.

Table 3. Assemblies with a plutonium core with no reflector and a high-enriched uranium shell

Experiment index from the Handbook	Location carried out	Experiment configuration	$(k_c$-$k_e)$ in %, KENO ABBN-93	$(k_c$-$k_e)$ in %, MCNP ENDF/B-V	$(k_c$-$k_e)$ in %, MCNP ENDF/B-VI
MIX-MET-FAST-001	LANL	Pu (5% ^{240}Pu) + 1.7 cm U (93%)	–0.39±0.16(8)	–0.20(8)	
MIX-MET-FAST-003	VNIIEF	Pu (9% ^{240}Pu) + 2.3 cm U (90%)	-0.15±0.16(10)	–0.01(6)	
Expected root-mean-square spread (δk_{exp})			±0.18	±0.17	
Observed mean divergence $(\Delta k \pm \delta k_{cal})$			–0.28±0.12	–0.09±0.10	

Table 4. Critical assemblies with a core of uranium-233 with no reflector in an enriched uranium shell

Experiment index from the Handbook	Location carried out	Experiment configuration	$(k_c$-$k_e)$ in %, KENO ABBN-93	$(k_c$-$k_e)$ in %, MCNP ENDF/B-V	$(k_c$-$k_e)$ in %, MCNP ENDF/B-VI
U233-MET-FAST-001	LANL	Sphere of ^{233}U	–0.44±0.10(8)	–0.30(11)	
U233-MET-FAST-002-1	LANL	Sphere of ^{233}U + 1.2 cm ^{235}U	–0.43±0.10(8)	–0.31(9)	
U233-MET-FAST-002-2	LANL	Sphere of ^{233}U + 2.0 cm ^{235}U	–0.28±0.11(8)	+0.07(9)	
Expected root-mean-square spread (δk_{exp})			±0.14	±0.14	
Observed mean divergence $(\Delta k \pm \delta k_{cal})$			–0.38±0.07	–0.18±0.18	

5. Uranium and plutonium spheres with a metallic uranium-238 reflector

Table 5 gives the criticality divergences between the calculation and the experiment for assemblies with a metallic uranium reflector and metallic cores of varying composition. All 22 critical states recommended for use as benchmarks for the analysis of programs and constants used for nuclear safety calculations were investigated. The calculated values of k_{eff}

for critical assemblies with no reflector were on average persistently lower than the experimental values, but the reverse was found for assemblies with a uranium reflector.

The data show that calculations using both the ABBN-93 constants and the ENDF/B-V constants overestimate the contribution of the uranium reflector to the multiplication coefficient. It should be noted that the energy spectra of the neutrons in the above-mentioned critical assemblies with no reflector containing plutonium and high-enriched uranium are similar to one another, as are the neutron importance spectra. There is therefore every reason to assume that the effect of the reflector on the criticality of both the uranium and plutonium assemblies will be almost identical.

Table 5. Critical Assemblies with a Metallic Uranium-238 Reflector

Experiment index from the Handbook	Location carried out	Geometry and thickness of reflector	(k_c-k_e) in %, KENO ABBN-93	(k_c-k_e) in %, MCNP ENDF/B-V	(k_c-k_e) in %, MCNP ENDF/B-VI
HEU-MET-FAST-014	VNIITF	Sphere, 4.65 cm	−0.07±0.17(7)	−0.07(6)	−0.31(6)
HEU-MET-FAST-029	VNIIEF	Sphere, 4.70 cm	+0.44±0.20(7)		
HEU-MET-FAST-003-1	LANL	Sphere, 5.08 cm	−0.52±0.50(7)	−0.50(8)	
HEU-MET-FAST-003-2	LANL	Sphere, 7.62 cm	−0.69±0.50(7)	−0.52(9)	
HEU-MET-FAST-003-3	LANL	Sphere,10.16cm	−0.03±0.50(7)	+0.07(11)	
HEU-MET-FAST-003-4	LANL	Sphere, 12.70 cm	−0.18±0.30(7)	−0.13(10)	
HEU-MET-FAST-003-5	LANL	Sphere, 17.78 cm	+0.11±0.30(7)	+0.28(10)	
HEU-MET-FAST-003-6	LANL	Sphere, 20.32 cm	+0.24±0.30(7)	+0.24(11)	
HEU-MET-FAST-003-7	LANL	Sphere, 27.94 cm	+0.30±0.30(7)	+0.41(12)	
HEU-MET-FAST-002-2	LANL	Cylinder, 20 cm	+0.35±0.30(7)	+0.30(10)	
HEU-MET-FAST-002-3	LANL	Parallelepiped, 4x4x3.66", 8"	+0.18±0.30(7)	+0.20(10)	
HEU-MET-FAST-002-4	LANL	Parallelepiped 5x5x2.53", 8"	+0.10±0.30(7)	+0.41(10)	
HEU-MET-FAST-002-5	LANL	Parallelepiped 3x3x7.56",8"	−0.04±0.30(7)	+0.39(10)	
HEU-MET-FAST-002-6	LANL	Parallelepiped 3x3.5x6.0",8"	+0.25±0.30(7)	+0.28(11)	
Expected root-mean-square spread (δk_{exp})			±0.30	±0.32	
Observed mean divergence $(\Delta k \pm \delta k_{cal})$			+0.11	+0.09	

Experiment index from the Handbook	Location carried out	Geometry and thickness of reflector	$(k_c\text{-}k_e)$ in %, KENO ABBN-93	$(k_c\text{-}k_e)$ in %, MCNP ENDF/B-V	$(k_c\text{-}k_e)$ in %, MCNP ENDF/B-VI
PU-MET-FAST-010	LANL	Sphere, 4.0 cm	–0.22±0.18(8)	+0.05(9)	
PU-MET-FAST-020	VNIITF	Sphere, 9.65 cm	+0.47±0.17(8)	+0.10(6)	
PU-MET-FAST-006	LANL	Sphere, 20 cm	*+0.06±0.30(8)*	*+0.47(14)*	
Expected root-mean-square spread (δk_{exp})			±0.21	±0.21	
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			+0.13	+0.14	
MIX-MET-FAST-002-1	LANL	Sphere, 2% ^{240}Pu, 19cm	+0.46±0.42(8)	+0.61(13)	+0.44(13)
MIX-MET-FAST-002-2	VNIITF	Sphere, 5% ^{240}Pu, 19cm	+0.48±0.44(8)	*+0.68(12)*	*+0.68(14)*
MIX-MET-FAST-002-3	LANL	Sphere, 16% ^{240}Pu, 19cm	+0.76±0.48(8)	+0.76(12)	+0.69(11)
Expected root-mean-square spread (δk_{exp})			±0.45	±0.45	±0.45
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			+0.55	+0.68	+0.67
U233-MET-FAST-003-1	LANL	Sphere of ^{233}U+^{235}U, 2.3cm	–0.31±0.10(8)	+0.03(9)	
U233-MET-FAST-003-2	LANL	Sphere of ^{233}U+^{235}U, 20cm	–0.31±0.11(8)	–0.44(9)	
U233-MET-FAST-006	LANL	Sphere of ^{233}U, 20cm	–0.44±0.14(8)	+0.23(11)	
Expected root-mean-square spread (δk_{exp})			±0.14	±0.14	
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			-0.34	-0.10	

For convenience, the averaging results from Table 5 and the relevant tables for assemblies with no reflector are summarised below.

Clearly, in all cases the calculated efficiency of the uranium reflector is high, though by an amount which is only a little greater than the error level. In view of the fact that the mean divergences between the calculation and the experiment in the criticality of the uranium and plutonium assemblies differ significantly, it was thought wise - for the purposes of eliminating errors in the computational description of the effect of the reflector on criticality - to cross-compare not the calculated and experimental values of k_{eff} for assemblies with reflectors of varying thickness, but the differences $\delta k_U = k_{eff}(\text{U-refl.}) - k_{eff}(\text{bare})$. Here the index U indicates the material of the reflector; k_{eff}(U-refl.) is the calculated or, as appropriate, experimental value of the multiplication coefficient for an assembly with a uranium reflector of a specific thickness; k_{eff}(bare) is the corresponding value for an assembly with no reflector with the same core material and studied at the same laboratory. There is a clear reduction in the error levels caused by inaccuracies in the determination of the composition and, in part, the dimensions of the core when determining the experimental differences, and the reflector effect becomes visible in a more or less pure form. Table 6 shows the divergences between the calculation and the experiment $\Delta k_U = \delta k_{U,c} - \delta k_{U,e}$ together with the experimental and calculation error levels. The last rows of the table give the same mean characteristics as in the preceding tables.

	ABBN-93	ENDF/B-V
Uranium assemblies with a uranium reflector	+0.11±0.30	+0.09±0.30
Uranium assemblies with no reflector	–0.29±0.17	–0.29±0.14
Difference	**+0.40±0.33**	**+0.38±0.33**
Plutonium assemblies with a uranium reflector	*+0.13±0.21*	*+0.14±0.21*
Plutonium assemblies with no reflector	*–0.31±0.20*	*–0.38±0.20*
Difference	***+0.44±0.29***	***+0.52±0.29***
Mixed assemblies with a uranium reflector	+0.55±0.45	+0.68±0.45
Mixed assemblies with no reflector	–0.28±0.20	–0.09±0.20
Difference	**+0.83±0.50**	**+0.77±0.50**
Assemblies containing uranium-233 with a uranium reflector	*–0.34±0.11*	*–0.10±0.11*
Assemblies containing uranium-233 with no reflector	*–0.38±0.11*	*–0.18±0.11*
Difference	***+0.04±0.20***	***+0.08±0.20***

Table 6 gives data only for spherical assemblies. What particular spherical assembly was taken as a basis in each case is indicated in the notes after the table. The descriptions of the evaluations very frequently do not give all the components of the error level ascribable to the experimental value of k_{eff}. Therefore, an accurate evaluation of the error level of the differences between the two experimental values of k_{eff} could only be performed in some cases. In the remaining cases, the error level of k_{eff} for an assembly with a reflector, or of k_{eff} for an assembly with no reflector, was used for the error level of this difference, depending on which of these two values was the greater. As above, the averaging of the unequally accurate results was performed employing a weighting which was inversely proportional to the total dispersion, which is equal to the sum of the squares of the experimental and calculation error levels. In the case of the differences, the contribution of the statistical error levels of the calculated results was often significant.

Table 6. Effect of a Metallic Uranium-238 Reflector

Experiment index from the Handbook	Location carried out	Reflector thickness	$(\delta k_{U.c}-\delta k_{U.c})$ % KENO ABBN-93	$(\delta k_{U.c}-\delta k_{U.c})$ % MCNP ENDF/B-V	$(\delta k_{U.c}-\delta k_{U.c})$ % MCNP ENDF/B-VI
U233-MET-FAST-003-2 (basis U3MF-001)	LANL	2.3 cm	+0.13±0.10(11)	+0.33(12)	
PU-MET-FAST-010 (basis PMF-001)	LANL	4.0 cm	–0.01±0.20(11)	+0.48(12)	
HEU-MET-FAST-014 (basis HMF-008)	VNIITF	4.65 cm	+0.29±0.17(11)	+0.48(6)	+0.33(6)
HEU-MET-FAST-029 (basis HMF-18)	VNIIEF	4.70 cm	+0.58±0.20(11)		–0.44(6)
HEU-MET-FAST-003-1 (basis HMF-1)	LANL	5.08 cm	–0.50±0.50(10)	–0.18(13)	
U233-MET-FAST-003-2 (basis U3MF-001)	LANL	5.3 cm	+0.13±0.10(11)	–0.14(12)	
HEU-MET-FAST-003-2 (basis HMF-1)	LANL	7.63 cm	–0.67±0.50(10)	–0.20(13)	
HEU-MET-FAST-003-3 (basis HMF-1)	LANL	10.16 cm	–0.01±0.50(10)	+0.39(14)	
HEU-MET-FAST-003-4 (basis HMF-1)	LANL	12.70 cm	–0.16±0.35(10)	+0.19(12)	
HEU-MET-FAST-003-5 (basis HMF-1)	LANL	17.78 cm	+0.13±0.35(10)	+0.60(12)	
MIX-MET-FAST-002 (basis MMF-1)*	LANL	18.9 cm	+0.96±0.40(11)	+0.88(14)	
U233-MET-FAST-006 (basis U3MF-1)	LANL	20 cm	0.00 ±0.14(10)	+0.53(15)	
PU-MET-FAST-006 (basis PMF-001)	LANL	20 cm	+0.27±0.40(11)	+0.90(19)	
HEU-MET-FAST-003-6= HMF-002 (basis HMF-1)	LANL	20.3 cm	+0.26±0.35(10)	+0.56(13)	
HEU-MET-FAST-003-7 (basis HMF-1)	LANL	27.9 cm	+0.32±0.35(10)	+0.73 (15)	
Expected root-mean-square spread (δk_{exp})			±0.25	±0.26	
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			+0.15±0.25 +0.11±0.38**	+0.33±0.30 +0.40±0.35**	

* Averaged results for three assemblies containing from 2.3% to 16% plutonium-240 (see text).

** Averaging results equal weightings given in brackets.

It should be noted that, in a series of cases, clearly not all factors were taken into account in the evaluation of the error levels of the experimental results. Thus, for example, the error level for uranium-233 assemblies with a reflector - according to the description - only takes account of error caused by inaccurate knowledge of the thickness of the reflector. There can be no doubt that the error level of the difference in the experimental values for k_{eff} with a reflector, and with no reflector, is significantly underestimated for all assemblies with uranium-233 in the core. On the other hand, in the description of the evaluation of the HEU-MET-FAST-003 series assemblies, it is noted that the fairly high error level ascribed to k_{eff}

reflects the opinion expressed by the experimenters several years after the experiments were completed. Comparison with the carefully evaluated error levels of other similar experiments leads us to the assumption that the experimenters greatly overestimated the error levels for this experimental series. Therefore, we tried a variant averaging process for the data which assumes that all the results have an identical accuracy level. These data are given in Table 5 in brackets.

Attention is drawn to the following:

1. Irrespective of whether the difference in the evaluated error levels of the experimental results is taken into account in the averaging, or whether all the data are considered to be equally accurate, the mean divergence between the calculated and experimental evaluation of the efficiency of the uranium reflector as shown by the data in Table 5 (0.2-0.3%) is significantly lower than was indicated above by the comparison of the mean divergence between the calculation and the experiment for all assemblies with a reflector and a uranium (or plutonium, or mixed) core and the divergence between the calculation and the experiment for all similar assemblies with no reflector (0.5-0.9%). This definitely indicates that there are correlations in the error levels for the experimental determination of k_{eff} in the same laboratory. When comparing the results with and without a reflector obtained at the same laboratory, the correlated error levels are lower (irrespective of whether the error levels were taken into account in the evaluation or not);

2. The mean divergence between the results of the calculation and the experiment is the same as the evaluated mean error level of an individual experiment and somewhat lower than the root-mean-square spread.

Thus, we may say that the calculated and experimental efficiency of a uranium reflector agree to within error limits (experimental error plays a decisive role). Within error limits, no significant systematic dependence of the divergence between the calculation and the experiment on the thickness of the uranium reflector is observed. This may be clearly seen in Fig.1 where the observed divergence are shown relative to reflector thickness.

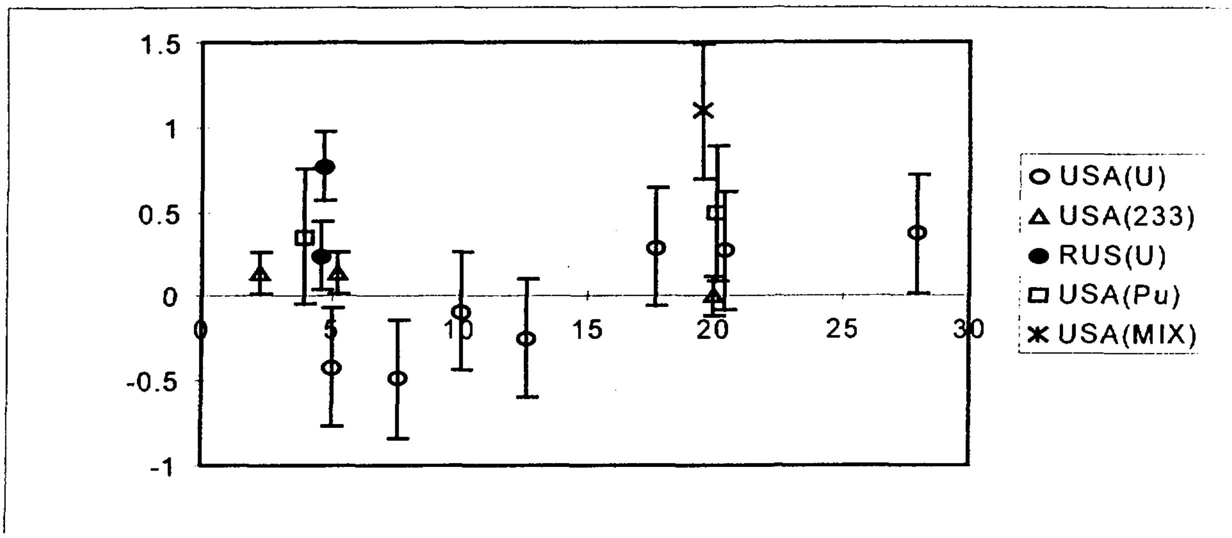

Fig. 1. *Dependence of the divergence (in %% Δk/k) between the calculated and experimental efficiency of a metallic uranium-238 reflector on reflector thickness.*

6. Critical assemblies with reflectors made of polyethylene or water

Nine assemblies of this kind were studied at four different institutes in Russia and the USA. The divergence between the calculation and the experiment for all these assemblies are shown in Table 7.

As we can see, the divergence between the calculated and experimental values for assemblies with polyethylene and water reflectors agree on average with an accuracy approaching the experimental and root-mean-square error levels, which are slightly larger.

Table 8 gives the divergences between the calculation and the experiment for the efficiency of the polyethylene and water reflectors $\Delta k_H = \delta k_{H,c} - \delta k_{H,e}$. These values are determined in exactly the same way as for the uranium reflectors. However, it should be noted that the polyethylene and water reflectors significantly soften the spectrum of the neutrons causing the fission in the core, and it is therefore not at all self-evident that the error levels for the calculated evaluation of the efficiency of these reflectors for both uranium and plutonium assemblies should be identical. Therefore, the mean characteristics of the divergences between the calculation and the experiment are given separately in Table 8 for three uranium and three plutonium assemblies and, finally, for all the spherical assemblies included in the Table. For the uranium assemblies, the ABBN-93 and ENDF/B-V constants can be used to predict the efficiency of the polyethylene reflectors to an accuracy within the expected error levels. The ENDF/B-VI constants yield a slight overestimation (one-and-a-half times the error level) of reflector efficiency. For the plutonium assemblies, only the ENDF/B-V constants describe the efficiency of the polyethylene reflectors to an accuracy within the error levels; the ABBN-93 constants and ENDF/B-VI constants yielded an overestimate of the efficiency three times the expected error level. However, the efficiency of the thick water reflector when calculated using the ABBN-93 and ENDF/B-V constants for an assembly with a plutonium core was practically identical, and coincided with the experiment within error limits.

Table 7. Critical assemblies with polyethylene or water reflectors

Experiment index from the Handbook	Location carried out	Geometry; reflector thickness	(k_c-k_e) in %, KENO ABBN-93	(k_c-k_e) in %, MCNP ENDF/B-V	(k_c-k_e) in %, MCNP ENDF/B-VI
HEU-MET-FAST-020	VNIIEF	Sphere; polyethylene 1.45 cm	+0.12±0.28(7)	−0.48(6)	−0.18(7)
HEU-MET-FAST-024	VNIITF	Sphere; steel 0.25 cm + polyethylene 10 cm	−0.62±0.15(8)	−0.40(7)	−0.31(7)
HEU-MET-FAST-011	VNIITF	Sphere; polyethylene 13 cm	−0.06±0.15(8)	−0.49(8)	−0.09(7)
HEU-MET-FAST-007-35	ORNL	Disk; 13x25x2.7 cm + polyethylene 15 cm	−0.61±0.01(8)	−1.26(18)	
PU-MET-FAST-031	VNIIEF	Sphere (10% ^{240}Pu); polyethylene 3.7 cm	+0.29±0.21(9)	−0.07(7)	+0.21(8)
PU-MET-FAST-027	VNIIEF	Sphere (2% ^{240}Pu); polyethylene 5.6 cm	+0.36±0.22(9)	−0.05(7)	+0.28(8)
PU-MET-FAST-024	VNIIEF	Sphere (2% ^{240}Pu); polyethylene 1.6 cm	+0.05±0.20(6)	−0.05(6)	+0.11(6)
HEU-MET-FAST-004	LANL	Sphere with thick water reflector	−0.03±0.15(8)	−0.20(5)	
PU-MET-FAST-011	LANL	Sphere (5% ^{240}Pu) with thick water reflector	−0.37±0.10(9)	−0.07(11)	
Expected root-mean-square spread (δk_{exp})			±0.15	±0.18	±0.20
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			-0.32±0.33	-0.34±0.23	0.00±0.21

Table 8. Efficiency of a spherical polyethylene or water reflector

Experiment index from the Handbook	Location carried out	Reflector thickness	$(\delta k_{CH2,c}-\delta k_{CH2,e})$ in %, KENO ABBN-93	$(\delta k_{CH2,c}-\delta k_{CH2,e})$ in %, MCNP ENDF/B-V	$(\delta k_{CH2,c}-\delta k_{CH2,e})$ in %, MCNP ENDF/B-VI
HEU-MET-FAST-020 [basis HMF-018]	VNIIEF	Polyethylene 1.45 cm	+0.26±0.30(12)	–0.32(9)	+0.21(10)
HEU-MET-FAST-024 [basis HMF-008]	VNIITF	Polyethylene 10 cm	–0.36±0.20(11)	+0.15(10)	+0.33(10)
HEU-MET-FAST-011 [basis HMF-008]	VNIITF	Polyethylene 13 cm	+0.30±0.20(11)	+0.06(11)	+0.55(10)
Expected root-mean-square spread for uranium assemblies (δk_{exp})			±0.25	±0.25	±0.24
Observed mean divergence for uranium assemblies $(\Delta k \pm \delta k_{cal})$			+0.03±0.27	-0.14±0.24	+0.39±0.14
PU-MET-FAST-031 [basis PMF-029]	VNIIEF	Polyethylene 3.7 cm	+0.82±0.20(12)	+0.49(10)	+0.62(11)
PU-MET-FAST-027 [basis PMF-029]	VNIIEF	Polyethylene 5.6 cm	+0.89±0.30(12)	+0.51(10)	+0.69(11)
PU-MET-FAST-024 [basis PMF-022]	VNIIEF	Polyethylene 1.6 cm	+0.32±0.20(6)	+0.30(9)	+0.52(9)
Expected root-mean-square spread for plutonium assemblies (δk_{exp})			±0.24	±0.24	±0.24
Observed mean divergence for plutonium assemblies $(\Delta k \pm \delta k_{cal})$			+0.61±0.26	+0.42±0.10	+0.60±0.11
HEU-MET-FAST-004 [basis HMF-001]	LANL	Thick layer of H_2O	–0.01±0.17(11)	+0.12(9)	
PU-MET-FAST-011 [basis HMF-001]	LANL	Thick layer of H_2O	–0.16±0.20(11)	+0.36(11)	
Expected root-mean-square spread for all assemblies (δk_{exp})			±0.21	±0.21	±0.24
Observed mean divergence for all assemblies $(\Delta k \pm \delta k_{cal})$			-0.08±0.07	+0.22±0.12	+0.50±0.24

Thus the whole set of available data hardly provides grounds for asserting that the overestimation of the efficiency of the polyethylene reflector noted above for plutonium assemblies is statistically significant. The mean characteristics of the divergences between the calculation and the experiment for all spherical assemblies, which are given in the last rows of Table 8, show that the mean divergence between the calculation and the experiment using both the ABBN-93 and ENDF/B-V constants does not exceed the root-mean-square spread.

7. Critical assemblies with iron reflectors

For assemblies with iron reflectors we only have Russian data. The VNIIEF produced data on the criticality of two spherical assemblies with a high-enriched uranium core and four spherical assemblies with a plutonium core. In addition, data are available on the criticality of the BR-1 reactor which has iron shielding (this is a quasi-cylindrical critical system). The divergences between the calculation and the experiment for these assemblies are given in Table 9.

Table 9: Critical assemblies with an iron reflector

Experiment index from the Handbook	Location carried out	Geometry; reflector thickness	$(k_c$-$k_e)$ in %, KENO ABBN-93	$(k_c$-$k_e)$ in %, MCNP ENDF/B-V	$(k_c$-$k_e)$ in %. MCNP ENDF/B-VI
IEU-MET-FAST-005	VNIIEF	Sphere (36%); reflector 8.25 cm	−0.02±0.21(7)	+1.35(6)	+0.00(6)
HEU-MET-FAST-021	VNIIEF	Sphere (90%); reflector 9.7 cm	−0.66±0.24(7)	+0.70(6)	−0.52(6)
PU-MET-FAST-025	VNIIEF	Sphere (2% ^{240}Pu); reflector 1.55 cm	−0.93±0.20(9)	+0.67(7)	−0.34(6)
PU-MET-FAST-032	VNIIEF	Sphere (10% ^{240}Pu); reflector 4.5 cm	−1.03±0.20(9)	−0.02(6)	−0.30(6)
PU-MET-FAST-026	VNIIEF	Sphere (2% ^{240}Pu); reflector 11 cm	−0.69±0.24(9)	+0.92(6)	−0.11(6)
PU-MET-FAST-028	VNIIEF	Sphere (2% ^{240}Pu); reflector 20 cm	−0.33±0.22(8)	+0.23(6)	−0.23(6)
PU-MET-FAST-015	IPPE[1]	BR-1 reactor with iron shielding	−0.06±0.27(8)	+0.17 (7)	
Expected root-mean-square spread (δk_{exp})			±0.24	±0.23	±0.21
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			-0.56±0.38	+0.58±0.46	-0.25±0.17

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[1] Institute of Physics and Power Engineering.

The data in the table show that only the calculations using the ENDF/B-VI constants describe the experimental data to an accuracy within the error levels. However, it should be remembered that the ENDF/B-VI constants did not prove similarly reliable in the analysis of the uranium and plutonium assemblies with no reflector. Therefore, for the iron reflector it is particularly important to examine the divergences between the calculated and experiment for the efficiency of the reflector, as was done above for the uranium and polyethylene reflectors. It should be borne in mind that calculating the efficiency of the iron reflector requires that the space dependence of resonance self-shielding of the iron cross-sections be taken into account. In the calculations using the MCNP program, this is done via a detailed description of the energy dependence of the neutron cross-sections in the resolved resonance region. In the calculations using the KENO program, the space dependence of resonance self-shielding is taken into account by using a large number of narrow energy groups, which allows the structure of the cross-sections in the vicinity of the strong *s*-resonances to be described in some detail. The unresolved resonance structure in the 299-group approximation (contribution of narrow *p*-resonances, the resonances at high energies, etc.) was taken into account using self-shielding factors, i.e. on average, without taking into account the space dependence of the self-shielding effect. Consequently, the albedo of the iron reflector may be slightly underestimated.

Table 10 gives data on the divergences between the calculated and experimental values for the efficiency of iron reflectors.

Table 10: Efficiency of iron reflectors

Experiment index from the Handbook	Location carried out	Geometry; reflector thickness	($\delta k_{Fe,c}$-$\delta k_{Fe,e}$) in %, KENO ABBN-93	($\delta k_{Fe,c}$-$\delta k_{Fe,e}$) in %, MCNP ENDF/B-V	($\delta k_{Fe,c}$-$\delta k_{Fe,e}$) in %, MCNP ENDF/B-VI
IEU-MET-FAST-005 [basis IMF-003]	VNIIEF	Sphere (36%); reflector 8.25 cm	–0.10±0.25(9)	+0.81(8)	–0.46(8)
HEU-MET-FAST-021 [basis HMF-018]	VNIIEF	Sphere (90%); reflector 9.7 cm	–0.52±0.25(9)	+0.86 (9)	–0.15(8)
PU-MET-FAST-025 [basis PMF-022]	VNIIEF	Sphere (2% ^{240}Pu); reflector 1.55 cm	–0.66±0.30(11)	+1.02 (10)	+0.07(9)
PU-MET-FAST-032 [basis PMF-029]	VNIIEF	Sphere (10% ^{240}Pu); reflector 4.5 cm	–0.50±0.30(10)	+0.54 (10)	+0.11(9)
PU-MET-FAST-026 [basis PMF-022]	VNIIEF	Sphere (2% ^{240}Pu); reflector 11 cm	–0.42±0.30(9)	+1.27 (10)	+0.30(9)
PU-MET-FAST-028 [basis PMF-029]	VNIIEF	Sphere (2% ^{240}Pu); reflector 20 cm	+0.20±0.30(10)	+0.79 (10)	+0.18(10)
Expected root-mean-square spread (δk_{exp})			±0.30	±0.30	±0.28
Observed mean divergence ($\Delta k \pm \delta k_{cal}$)			-0.33±0.28	+0.88±0.21	+0.01±0.25

As may be seen from the above data, the ENDF/B-VI constants undoubtedly predict the efficiency of the iron reflector better than ENDF/B-V (use of the latter library causes significant overestimation of reflector efficiency). The ABBN-93 constants yield a reflector efficiency which is slightly lower than the experimental value, but this difference is significantly smaller than the error level of the experiment.

8. Conclusions

The fulfilled analysis shows that the calculations using the ABBN-93 constants underestimate k_{eff} for bare plutonium assemblies by -0.3±0.2%, and k_{eff} for uranium-233 spheres by -0.4±0.2%. No correlation of the divergence with the plutonium-240 content was observed. For bare high-enriched uranium assemblies, the calculated values of k_{eff} were also on average -0.25% lower than the experimental values but, since the root-mean-square spread of the experimental data has the same value, we may assume that the results of the calculations agree with the experimental data to within error limits.

The calculations with the ABBN-93 constants can be used to describe the efficiency of reflectors made of metallic uranium-238, iron and polyethylene and water to an accuracy within the experimental error levels.

REFERENCES

[1] MANTUROV, G.N., NIKOLAEV, M.N., TSIBOULIA, A.M., "BNAB-93 Group Data Library. Part 1: Nuclear Data for Calculation of Neutron and Photon Radiation Fields", INDC (CCP)-409/L, IAEA, Vienna (1997), 65-110.

[2] MANTUROV, G.N., NIKOLAEV, M.N., TSIBOULIA, A.M., "The ABBN-93 Group Constants System: Verification Report No. 1", State Information Service, Moscow (1995).

[3] International Handbook of Evaluated Criticality Safety Benchmark Experiments. OECD - Nuclear Energy Agency, NEA/NSC/DOC(95)03 (September 1997 Edition).

[4] CAPELL, B.M., MOSTELLER, R.D., PELOWITZ, D.B., "MCNP Calculations for Russian Criticality-Safety Benchmarks", Proceedings of the Topical Meeting on Criticality Safety Challenges in the Next Decade (September 7-11, Chelan, Washington), 384-392.